

# Earthquake Risk Assessment Using Integrated Influence Diagram–AHP Approach

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**Abstract.** Indonesia is located at the joint situation of four major world tectonic plates in the Pacific Ring of Fire. Mostly, the coastal regions of Indonesia are highly prone to several natural hazards, such as tsunamis, earthquakes, and volcanic activity. The major earthquake incident in the country was the 2004 tsunami in Aceh, whereas a major volcanic eruption was the Mount Merapi volcanic eruption in 2010. With the present advancement of knowledge regarding the existing hazards, we acknowledge the importance of vulnerability and risk in monitoring and mitigating earthquake hazards. However, to date, a specific effort is unavailable for assessing the risk of earthquake hazards that will cover the city-level in Indonesia. Moreover, a comprehensive profile for risk assessment has yet to be created for small-scale urban areas. Few studies have been organized in Indonesia on city-scale risk assessment. Therefore, we attempt to fill this gap by calculating the risk percentage of Banda Aceh City by determining its conditioning factors and analyzing its variations spatially. We used an influence diagram approach and considered all the factors that affect the risk in Banda Aceh. Results show that only the central parts and some parts in the surrounding areas are under high risk compared with other locations. We validated the results using inventory earthquake events and results.

**Keywords:** Earthquake; Risk; GIS; ID–AHP approach

## 1. Introduction

From the past decades, several parts of Indonesia have experienced a number of disastrous events, such as the 2004 Indian Ocean tsunami, which destroyed half of Banda Aceh City and Nias, the 2006 tsunami in southern Java and the 2009 earthquake in Padang area took place. Specific key tools for measuring risk and identifying indicators and criteria are unavailable [1]. However, risk assessment considers several sets of indicators because such indicators depend on tectonic setting or context and might not be similar in other settings [2]. Common individual, building, social and geotechnical characteristics can be considered for risk assessment [2, 3, 4, 8]. Risk is also influenced by income distribution, access to economic assets and social security [1].

In the aftermath of the destructive earthquake and tsunami in Banda Aceh and Nias in 2004, risk assessments have been conducted in Indonesia [5]. However, these assessments have limited coverage and scope. Ref. [6] assessed risk and social vulnerability in Padang City; Ref. [7] analyzed social vulnerability to the volcanic eruption of surrounding areas of Merapi volcano; and Refs. [9] and [10] analyzed vulnerability and risk in seismic-prone areas in Bantul District. Some risk reduction procedures could consider all possible scenarios of events with frequency, that could be implemented using probabilistic approach of modelling. The prioritization of regions could be clearly enabled by these kind of analysis or building classes for the interventions of risk reduction. Valcárcel et al. (2013) applied this analysis to understand and assess the earthquake retrofitting effectiveness for schools in

South and Central America. However, they implemented a probabilistic earthquake risk assessment model to estimate the expected losses by focusing the schools portfolio and the rebuilding interventions or retrofiting. Through the probabilistic approach, risk reduction could be performed which is by creating the insurance pools. Therefore, the financial mechanisms could help in reducing the reconstruction burden and economic loss for residents and local governments through the risk transfer from the the financial to the insurance market. Therefore, several insurance companies could be found in the highly disastrous zones of Indonesia. Some additional finance plans could also help in reducing recover time from the damages originated due to earthquake.

To date, no appropriate and systematically coordinated progress exists for profiling the vulnerability and risk to earthquakes within the country, and the progress in damage prevention and losses are not supported by important information about earthquake risk. This study attempts to fill this gap by analyzing earthquake risk to natural hazards at the city level, identifying its major factors and analyzing the spatial variation among different parts of the city.

## 2. Materials and methods

### 2.1. Study area

Banda Aceh is the capital city of Aceh Province in Indonesia. It is located at the tip of North Sumatra and called the place for strategic, trading and transportation hub in the Indian Ocean. The city extends in an area of 61.36 km<sup>2</sup> (23.69 mi<sup>2</sup>). The city is composed of sandstones and loose quaternary sedimentary rocks with a maximum height of 0–10 m (0–32.9 ft) from the MSL. The total population of the city is approximately 356,983, and the estimated density is 5,800/km<sup>2</sup> (15,000/mi<sup>2</sup>). The city experienced an earthquake and tsunami during the 2004 Indian Ocean earthquake. Given that the area is characterized by loose geological sedimentary rocks, the city experiences high ground shaking.

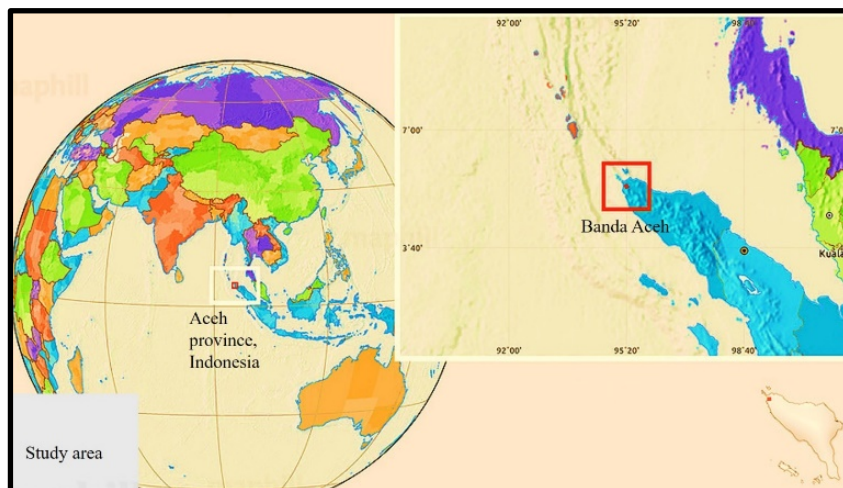


Figure 1. The study area (Source: Political location map, Banda Aceh).

### 2.2 Materials

On the basis of the recent literature review on earthquake risk assessment in Indonesia, all the data have been collected from the Badan Pusat Statistik (BPS), and 13 variables were selected in this study to produce the earthquake risk map. The data collected from different sources were utilized to produce a high-quality risk map. The experienced earthquake incidents were collected from the USGS website and applied for validation. Data were collected from the 2010 Survei Sosial Ekonomi Nasional, as shown in Table 1, and from the 2010 census provided by the BPS-Statistics Indonesia.

Table 1. Data used in this study.

Characteristic	Value	Percentage
Population	237.6 million	-
Annual growth rate	1.49 percent	-
Population density	124 people/km <sup>2</sup>	-
Person over 65	12.0 million	5.04
Children under 5	22.7 million	9.54
Adult illiterate	16.8 million	7.09
Poor people	31.0 million	13.3
Human development index	72.27	-

### 2.3 Methodology.

#### 2.3.1 Integrated influence diagram (ID)–analytic hierarchy process (AHP) approach

An ID is a visual display of a problem for decision making. It includes objectives, elements, uncertainties and decisions as to the nodes of the process. These building nodes of the ID are integrated with the AHP approach to producing a risk map. Satty’s AHP projects a meaningful structure on decision-making processes, where although some limited number of choices can be found, each is characterized by a number of attributes [11]. The use of ID is described in the flowchart in Figure 2.

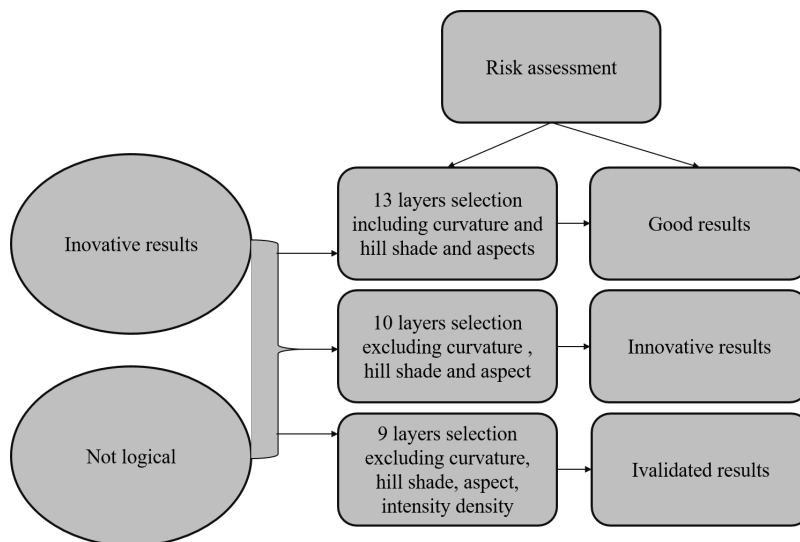


Figure 2. ID flowchart.

#### 2.3.2. Steps of AHP approach

Analytical hierarchy process (AHP) is a flexible and powerful approach for the decision making of choosing criteria. The scores and final ranking could be calculated by employing the pairwise relative

evaluations technique by using criteria and the alternative options provided. However, the calculations obtained by the AHP requires the decision maker's experience and the experts opinion. Therefore, the AHP approach could be considered as a tool which could able to convey the both qualitative and quantitative evaluations. Therefore AHP approach comes under the multicriteria decision making models. Moreover, the AHP is simple because its not necessary to create a complex expert system where the knowledge of the experts were embedded in it. However, in order to solve a big problem the AHP may need a large number criteria or alternatives for the evaluations by the user. Although AHP evaluation is easy and simple, however, it depends on the decision maker to express the relationship and comparison between options. The load of the evaluation will be unreasonable if experts opinion on criteria comparison were not properly conducted. Quadratically, the pairwise comparisons depends on the number of options and criteria which increases with increase of numbers. For example, if we are making the comparison among 4 criteria and 10 alternatives, then  $4 \cdot 3 / 2 = 6$  comparisons are needed to create the weight vector, and to develop a score matrix,  $4 \cdot (10 \cdot 9 / 2) = 180$  pairwise comparisons required.

Defining the problem and specifying the desired solutions.

1. The hierarchy is created by leveling the problem from general to specific.
2. Pairwise comparison matrices are constructed, and the indicators are compared with the alternatives at a superior level [11].

$$AW = l_{max}W, (1)$$

Where A denotes the pairwise matrix, W is the eigenvector,  $l_{max}$  is the largest eigenvalue and X is the eigenvector of the consistency matrix.

$$(A - l_{max}I)X = 0 (2)$$

3. All judgments are required to develop the metrics.
4. The reciprocals are entered into specific criteria diagonally.
5. Hierarchy composition is used to weigh the priority vectors with the criteria weights.
6. Consistency evaluation is conducted for the entire hierarchy by multiplying the consistency index with the priority of criterion [1].

The consistency index can be calculated as follows:

$$CI = (\lambda_{max} - n) / (n - 1). (3)$$

The consistency ratio can be calculated as

$$CR = CI / RI. (4)$$

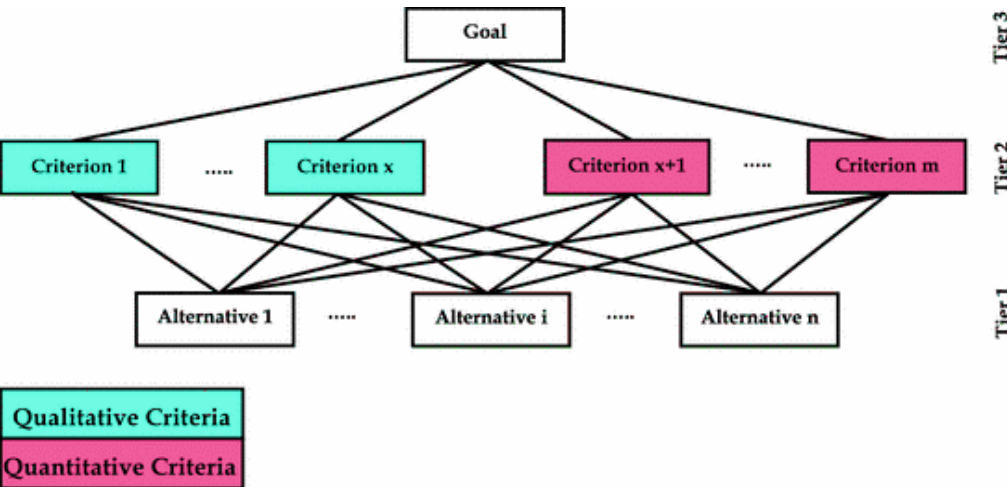


Figure 3. The general framework of AHP approach.

### 3. Results and Discussion

The results of the AHP approach results, the analysis of the priority coefficients of criteria and the pairwise comparisons of the sub-criteria that come under geotechnical, structural and social vulnerability are presented in Figure 4. The figure also expresses the focal point of this study. The Earthquake vulnerability map shows that the central part of the city is more vulnerable than the surrounding areas. It also indicates that the central and southern parts are characterized by high-density buildings, important educational institutions, and main transportation nodes.

By considering the response-ability of Banda Aceh City, we estimated its risk areas and classified them into five (Figure 5). The southern-central region is the riskiest (Figure 4). The entire city was also classified into nine zones. Regions 5, 3 and 7 are characterized as very high- to high-risk zones in order of ranks, respectively. Regions 2, 6 and 8 are high to moderately risky areas in the city, whereas the other regions, namely, Regions 9, 4, 1 and some parts of Region 3, have moderately to very low-risk areas. The risk areas are normally distributed throughout the city. Thus, the density of the population and buildings are high in the city center compared with the surrounding areas. The construction and urban condition are approximately similar throughout the city, thereby making all possible plans easy to apply after a crisis. As the entire city is composed of very loose sedimentary rocks, the coastal areas have more potential for ground shaking than the city center. However, the coastal areas are low risk because they have small buildings and population density. The calculated value indicates that some specific earthquakes above magnitude 6 can damage approximately 60%–70% of the total buildings. These earthquakes have the capacity to destroy 3%–25% of the population of Banda Aceh City.

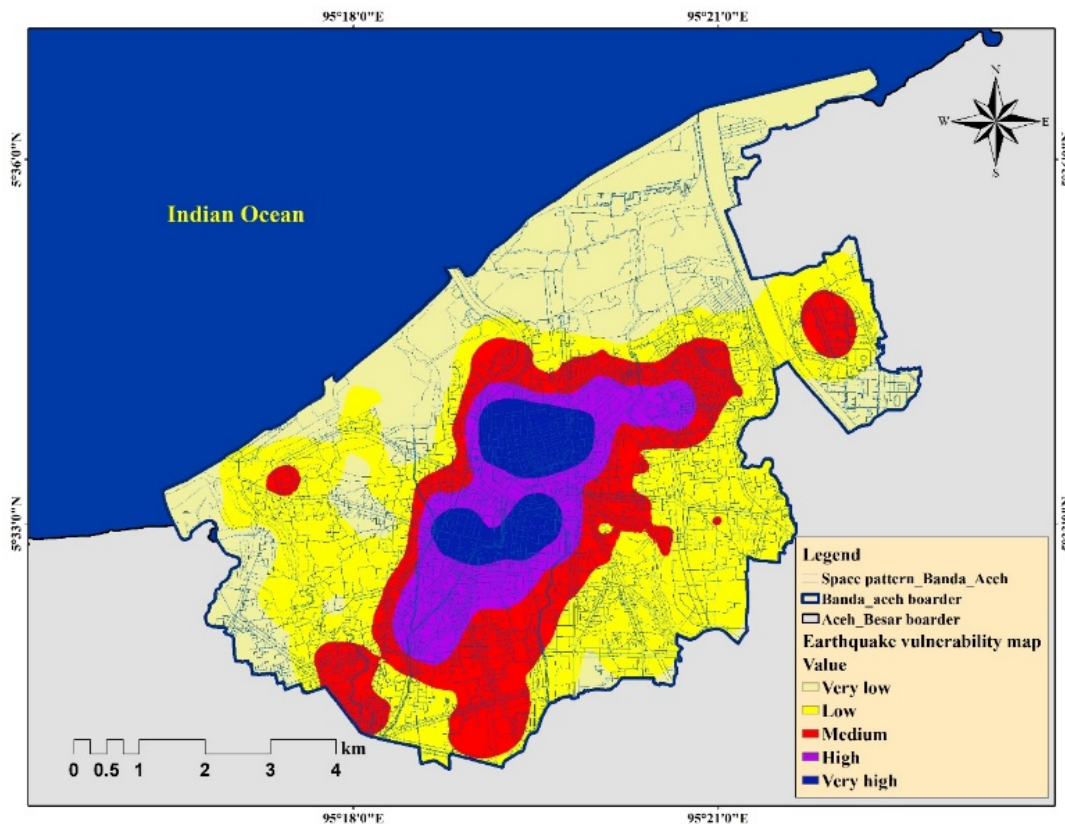


Figure 4. Earthquake vulnerability map.

Therefore, in view of the situations in Banda Aceh City, the Indonesia government should focus on measures and programs for reducing earthquake effects, such as:

- (i) Application of building regulations;
- (ii) Setting and implementation of land use laws;
- (iii) Application of safety rules in high-rise buildings and control of hazardous materials in buildings;
- (iv) Program organization to reduce the risks on buildings and lives of the people;
- (v) Organizing programs related to the protection of public service, including power supply protection and systems of telecommunications; and
- (vi) The organization of programs related to infrastructure network development, and creation of strategies with freeways away from vulnerable areas.

Ref. [5] described city inhabitants as extremely important in a community for which the highest priority should be considered and focused on the living body from every corner of mitigation planning. Moreover, the relationship between the lives of the people and developing city infrastructure is direct. However, Banda Aceh City has a high chance of experiencing more than 7-magnitude earthquakes in the future because it is falling in a seismic gap. Ref. [1] indicated that if accessible elements, such as rails, roads, stations, and old infrastructure, are damaged partially or fully and not accessible after a devastating earthquake, then rescue teams cannot save people safely, thereby magnifying the damage percentage. Therefore, old infrastructure and newly constructed buildings in the city must be given focus, controlled strictly and surveyed immediately to be functional after experiencing a disaster. Risk assessment and immunization should be applied in urban texture and zonation scale to reduce earthquake effects. Systematically, the currently developed approach must be implemented to perform earthquake crisis management at local and global scales. To do so, Banda Aceh City was selected and analyzed, and the obtained results were presented as a case to review and assess the risk of nine classified zones in the risk map.

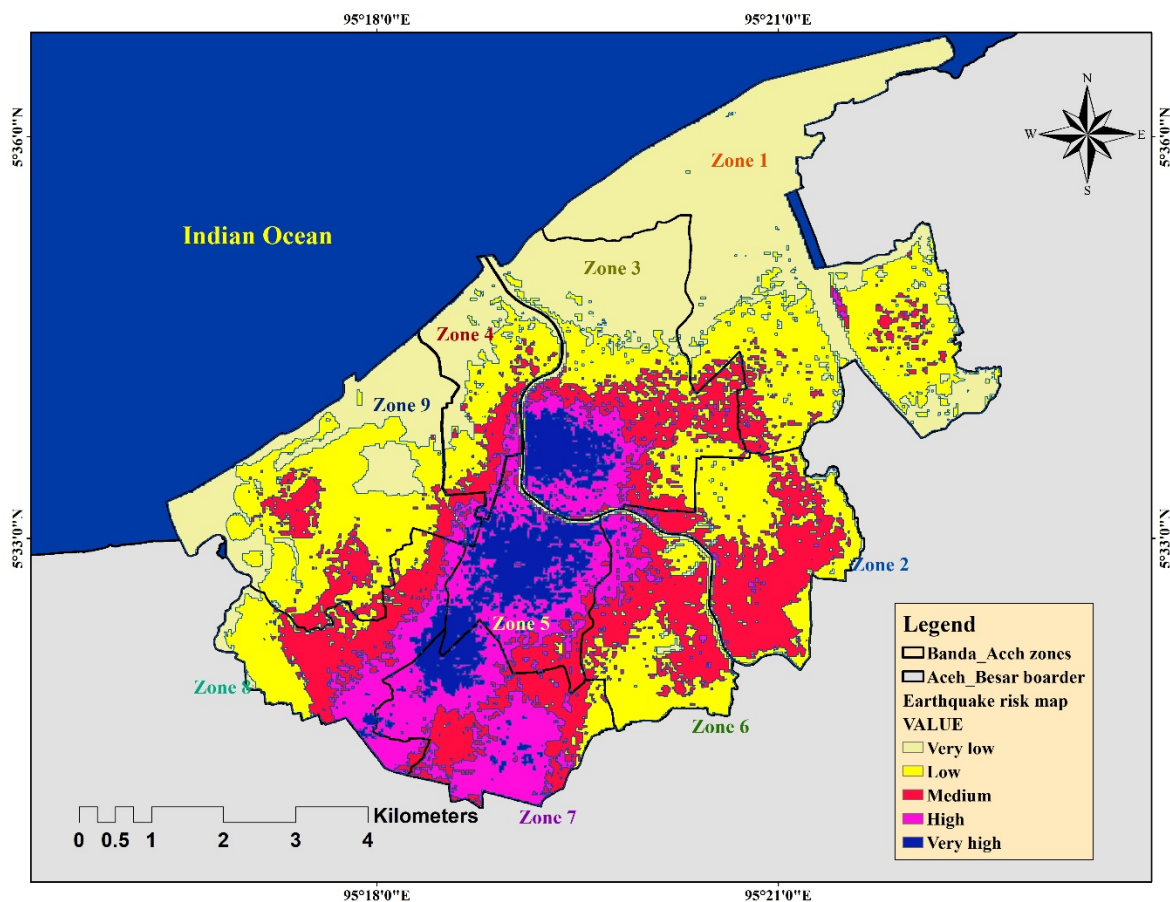


Figure 5. Earthquake risk map developed using the integrated ID–AHP approach.

#### 4. Conclusion

We can conclude from the obtained results from the nine zones of Banda Aceh City, three are considered very high-risk zone. After a crisis, the responsiveness of urban texture and relief possibility should be the major focus of the Indonesian government. City reversibility must be also given focus for mitigation planning during the crisis period. The ID–AHP approach for risk evaluation in the current analysis shows that natural hazard management is important in terms of managing. Planning and preparations for earthquake hazard management are needed to be done as early as possible because valuable property and human life are threatened in a short period of time. Society is characterized by anomalies and irregularities because real-life situations are exacerbated by natural hazards. Therefore, planners and urban managers should produce a hazard management framework based on inventory data and results to prevent damages and human and financial losses in the future. Complex software packages are required for assessing and estimating the earthquake hazards and risk using the complex components described in the dat section. Some publicly available open assess softwares could be found online. The current research all over the world demonstrated that how hazard and risk information could be useful to develop ultimately risk reduction measures and useful to mitigate the earthquake effects.

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